

Charm tagging and the $H \rightarrow W^+W^- \rightarrow \nu c j$ semi-leptonic channel

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We introduce a method to discover the Higgs boson at the Large Hadron Collider (LHC) through its decay to W^+W^- , where one boson decays to leptons, and the other decays to c +jet. This mechanism is complementary to the decay into dileptons, but has the potential to measure the invariant mass peak of the Higgs boson, and to avoid large recently discovered QCD backgrounds from heavy flavor decays. In addition, this mechanism motivates the study and creation of a dedicated charm jet tagger at LHC experiments. Existing charm jet tagging, in the form of fakes to bottom jet tagging, provides sensitivity to a standard model Higgs boson that is comparable to WW fusion. A 50% charm tagging efficiency in the relevant kinematic range could allow an independent 5σ discovery of a 165 GeV Higgs boson in 7 fb^{-1} of integrated luminosity at a 14 TeV machine, or exclusion with a 7 TeV collider.

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I. INTRODUCTION

The Higgs boson is the only particle of the standard model that has not been discovered. The ATLAS and CMS experiments at the Large Hadron Collider (LHC) search for a standard model-like Higgs boson through its decay to pairs of W bosons for masses of $140 \text{ GeV} \lesssim m_H \lesssim 200 \text{ GeV}$ where both W bosons decay leptonically [1, 2]. While $H \rightarrow WW \rightarrow l^+l^-\nu\bar{\nu}$ has been the dominant search mode in this mass range for more than a decade [3–5], there are two challenges associated with the dilepton plus missing energy \cancel{E}_T search. First, the loss of two neutrinos means that a Higgs mass cannot be directly reconstructed; instead it relies on a solid understanding of the measured kinematic variables in the presence of radiation effects and backgrounds [1, 2]. Second, it has been shown that at higher instantaneous luminosities there is a large and poorly determined background due to heavy-quark decays into isolated leptons that can be eliminated through the use of tighter cuts [6]. In this paper we propose the use of a complementary final state of Higgs boson decay, $H \rightarrow WW \rightarrow \nu c j$, which avoids both of these issues, and with improved charm tagging, could have a sensitivity for discovery comparable to the dilepton+ \cancel{E}_T search.

The semi-leptonic decay channel $H \rightarrow W^+W^- \rightarrow \nu jj$ has been studied previously in the literature and was found to be not promising for low masses due to the large Wjj background [5]. For large masses (typically 300 GeV and above) Higgs boson studies [1] predict reduced backgrounds, and νjj forms one of the main channels for discovery. Recent interest in this channel at lower masses has been ignited by Ref. [7], which demonstrated the existence of angular correlations in the νjj channels between the plane of the jets and the leptons that may help reduce the Wjj background. Nevertheless, the

Wjj background is still significant, and makes a discovery in the νjj final state difficult. In this paper we identify a key ingredient is the use of charm jet tagging to pick out the final state in which one of the jets contains a charmed hadron. With this addition, the Wjj background is greatly reduced. Furthermore, by identifying the charm jet, a unique assignment can be made to the angular correlations between all four decay products — allowing for much stronger cuts that enable a clean extraction of the $\nu c j$ signal, and a reconstruction of a Higgs boson mass peak.

The essential ingredient to measuring Higgs boson production in the semi-leptonic channel is the use of charm tagging. Currently there are no dedicated reconstruction algorithms for charm jet tagging in the public ATLAS or CMS analysis codes. However, charm jets are already reconstructed as fakes to “bottom jets” at roughly a 10–15% rate [8, 9]. A second goal of this paper is to advocate for the creation of a dedicated charm tagger with an acceptance of closer to 50%. Beyond enabling the discovery of a Higgs boson, a charm tagging capability is important for many other processes. As the first measurement of Wc has shown [10], the ability to identify charm leads to important constraints on the s parton distribution function [11]. In models of supersymmetry, a light top squark can decay to charm via a flavor-changing neutral current $\tilde{t} \rightarrow c\tilde{\chi}_0$ [12]. In the so-called “buried Higgs” scenario it is possible for a Higgs boson to decay to four charm quarks [13]. In this paper we consider a continuum of scenarios: from the use of charms currently mistagged as “ b jets”, through use a dedicated “ c -jet” tagger with roughly a 50% acceptance. We find in all cases that a 100% acceptance of events with of b quarks faking c jets does not change our results.

We describe the two key ingredients of our analysis, charm tagging and angular correlations in Sec. II. In Sec. III, we discuss a detailed list of cuts to reconstruct a Higgs boson peak above background. We then present the expected signal significance at a 14 TeV LHC for a range of charm jet tagging efficiencies, and contrast

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the results with the exclusion reach at a 7 TeV LHC. We conclude with a summary of key points and future directions.

II. CHARM TAGGING AND ANGULAR CORRELATIONS

The key ingredient of the search for the Higgs boson in the dilepton+ \cancel{E}_T channel is the use of the angular correlations between the outgoing charged leptons to reduce the background coming from direct W^+W^- production. Because the Higgs boson is a spin-0 particle, the spins of the W bosons are anti-aligned. The $V-A$ structure of W boson decay causes the W spin information to be manifest in the correlated angular distributions of the decays to leptons as seen in Fig. 1. Specifically, the cross section is enhanced when the charged leptons are aligned. There is also an enhancement when the neutrinos align, however, the standard dilepton+ \cancel{E}_T analysis cannot make full use of this correlation as the neutrinos are unobserved.

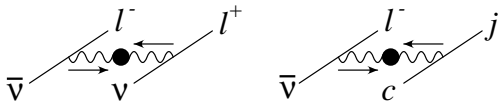


FIG. 1: Angular correlation between leptons in (left) $H \rightarrow W^-W^+ \rightarrow l^-\bar{\nu}l^+\nu$ and (right) $H \rightarrow W^-W^+ \rightarrow l^-\bar{\nu}cj$ due to the anti-alignment of W boson spins in Higgs boson decay.

The advantage of the charm-tagged semi-leptonic decay of the Higgs boson is apparent in Fig. 1, where we see that by identifying the charmed jet, we may take advantage of both the correlation between the charged lepton and the light-quark jet, and the correlation between the charmed jet and the neutrino in the event. Despite the fact that the neutrino appears as missing energy, we examine cases where it comes from an on-shell W decay, and can reconstruct its four-momentum up to a two-fold ambiguity in rapidity.

One goal of this paper is to spur development of a dedicated c -jet tagging algorithm in the model of existing b -jet tagging algorithms. In fact, c -jets are already tagged as “fakes” in the b -tagging algorithms. Hence, we model the transverse energy E_T dependence of the tagging efficiency utilizing existing impact-parameter b -tagging algorithms from CDF Run I [8] (as appear in PGS 3.2 and earlier), and Run II (as appear in PGS 4) [9]. Our main results use a function of the form

$$\epsilon_c^1 = k_c \times 0.2 \tanh\left(\frac{E_{Tj}}{42.08 \text{ GeV}}\right). \quad (1)$$

This function (shown in Fig. 2) is a scaled version of the PGS 3.2 impact-parameter efficiency for a c -jet to fake a b -jet [8]. In this paper we vary k_c between the Run I value of $k_c = 1$, and an enhanced value of $k_c = 5$ to extract the net reach with different charm tagging efficiencies. The

algorithm above is predominantly a fit to distributions of events in impact-parameter vs. track invariant-mass [14], and has the most room for adaptation to a dedicated charm tagger.

In order to calculate the backgrounds, we utilize a b -tagging efficiency of the form $\epsilon_b = k_b \times 0.6 \tanh(E_{Tb}/36.05 \text{ GeV})$, with $k_b = (k_c + 3)/4$ in order to model saturation of b acceptance. For light jets we take an efficiency of $\epsilon_j = 1\% \times 10^{(k_c-5)/4}$, which corresponds to a range of 0.1%–1%. When $k_c = 5$, the light-jet fake rate is scaled up over a factor of 10 vs. the baseline Tevatron rate at low jet E_T . In Sec. III we will see we are completely dominated by backgrounds involving charm jets, and hence, the details of the b and light-jet backgrounds are less important.

As a check of our main results, we have reproduced all numbers using a CDF Run II-like algorithm ϵ_c^2 from PGS 4. The E_T dependence of the charm tagging efficiency ϵ_c^2 is shown in Fig. 2 (scaled by a factor of 4). Despite the different E_T dependence, we find exactly the same significances after cuts as the backgrounds tend to have harder jets. Since the dominance of charm-initiated processes is insensitive to the details of the charm tagging algorithm, we present numerical results using ϵ_c^1 .

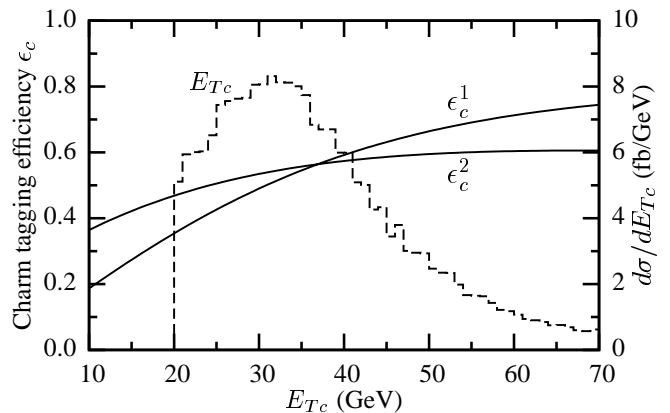


FIG. 2: Charm tagging efficiency curves and characteristic charm jet E_{Tc} from $H \rightarrow WW \rightarrow l\nu cj$ decay. $\epsilon_c^1(\epsilon_c^2)$ are CDF Run I(II)-like algorithms scaled up by a factor of 4.

An important consideration evident in Fig. 2 is that the typical charm E_T is about 20–40 GeV. Therefore, the effective charm tagging efficiency used in this analysis is $\epsilon_c \sim 12$ –48%. We emphasise an algorithm that improves charm tagging *acceptance* at such characteristic E_T 's is the relevant efficiency and not the asymptotic value. Neither 100% acceptance of b jets as “fakes” of charms, nor a factor of 3 change to the light-jet fake rate, materially change our results. However, we maintain a separate list of backgrounds so that our predictions may be rescaled to whatever efficiencies a dedicated charm tagger eventually obtains.

TABLE I: Next-to-leading order K -factors (after acceptance cuts) for the signal and backgrounds at a 14 TeV LHC.

Signal	Wcj	WW	$t\bar{t}$	Wbj	t(s)-chan. single top	$Wc\bar{c}$	$Wb\bar{b}$	Wjj
1.3	1.07	2.04	1.44	2.02	0.96(1.4)	1.6	1.6	1.07

TABLE II: Next-to-leading order K -factors (after acceptance cuts) for the signal and backgrounds at a 7 TeV LHC.

Signal	Wcj	WW	$t\bar{t}$	Wbj	t(s)-chan. single top	$Wc\bar{c}$	$Wb\bar{b}$	Wjj
1.86	1.36	1.39	1.44	2.1	1.04(1.54)	2.1	2.1	1.36

III. SIMULATION AND RESULTS

This analysis makes use of angular correlations, and proposes the creation of a charm tagging algorithm. In order to accurately model angular correlations we use the MadEvent 4.4 [15] event generator. We shower the events with PYTHIA 6.4 [16] and use the PGS 4 [9] detector simulation to reconstruct leptons and jets. The tagging efficiencies in PGS are replaced with the ones listed in Sec. II. Events are generated for $\sqrt{S} = 7$ TeV and $\sqrt{S} = 14$ TeV pp colliders using CTEQ6L1 parton distribution functions (PDFs) [17]. In contrast to the dilepton studies, we allow an additional jet to be in the event — consistent with the effects of next-to-leading order (NLO) radiation.

We normalize our cross sections to the NLO cross sections obtained after acceptance cuts applied in MCFM 5.8 [18] using CTEQ 6.5 PDFs [11]. Effective K -factors after cuts are shown in Tables I and II. The effective NLO K -factor at 14 TeV of 1.3 for $H \rightarrow WW$ after cuts is significantly smaller than the inclusive K -factor of 1.9 used by the ATLAS Collaboration [1]. Use of this smaller K -factor increases our estimates of the required luminosity for 5σ discovery by a factor of 2.1 with respect to the published experimental predictions for other Higgs decay modes at the LHC [1, 2]. Also note that K -factors for Wbj , Wcj and $Wc\bar{c}$ are estimated from jets.

The starting point for this analysis is the reconstruction of one isolated lepton (an electron or muon), and two or three jets with a single charm tag. The angular correlations in the Higgs signal tend to force the lepton and leading non-tagged jet to be close in phase space. Hence, we reconstruct jets using the PGS jet cone algorithm with a cone size of 0.4. The following acceptance cuts are used to define jets and leptons:

$$E_T^j > 20 \text{ GeV}, |\eta_j| < 2.5; p_T^l > 20 \text{ GeV}, |\eta_l| < 2.5. \quad (2)$$

Missing transverse energy \cancel{E}_T is reconstructed from the calorimeter and corrected for muons.

The standard model backgrounds for the semi-leptonic mode of $H \rightarrow lcj + \cancel{E}_T$ are Wcj , Wbj , Wjj , $Wc\bar{c}$, $Wb\bar{b}$,

W^+W^- , t - and s -channel single top, and $t\bar{t}$. The requirement of 2 or 3 jets and 1 charm tag in the final state reduces the $t\bar{t}$ background significantly. Charm tagging also substantially reduces the Wjj background, leaving Wcj as the dominant background at every level of cuts. Since the Higgs decay signal and the Wcj and $Wc\bar{c}$ backgrounds scale with the charm tagging efficiency ϵ_c , the signal over background S/B is nearly independent of the charm tagging efficiency. Hence, whatever efficiency is actually obtained by the experiments will only change the required integrated luminosity for discovery, and will not change the analysis. We demonstrate this point explicitly below.

Our event selection begins with a sequential set of “common cuts” listed in the top half of Tab. III. We require 2 or 3 jets, with 1 charm tag and a lepton. We require $\cancel{E}_T > 20$ GeV, and reconstruct the neutrino four-momentum p_ν by fitting the lepton and \cancel{E}_T to an on-shell W boson mass. We take the smallest absolute rapidity $|\eta_\nu|$ solution to complete the fit. The requirement that the leptonically decaying W boson be on-shell causes a significant loss of signal for Higgs bosons below WW threshold, but it is necessary to reconstruct the Higgs invariant mass.

As Wcj is the most problematic background, we tune most cuts to reduce its contribution. In the Wcj background, the transverse energy of the charm jet E_{Tc} and transverse momentum of the lepton p_{Tl} have a harder spectrum than the signal. We therefore impose cuts on the maximum values these variables can take: $E_{Tc} < 80$ GeV; $p_{Tl} < 60$ GeV. These values are optimal for a 160 GeV Higgs boson, but could be loosened in a more optimized fit for larger-mass Higgs bosons. In the Wcj background, $\Delta\eta_{cj}$, the pseudorapidity between the charm jet c and leading non-tagged jet j , has a slightly broader distribution than in the Higgs signal. Hence, we require $|\Delta\eta_{cj}| < 2$.

The backgrounds that are independent of charm tagging — $Wb\bar{b}$, Wbj , $t\bar{t}$, and single top — can be reduced significantly by using the angular correlations between the final state particles. The simplest angular cuts, are those similar to that of $\Delta\phi_{ll}$ in the leptonic channel, where we cut on the equivalent $\Delta\phi_{jl} < 2$ between the lepton l and *leading* non-tagged jet j . In addition, we know that the directions of the neutrino and c -jet are correlated. Therefore we can also make a cut $\Delta\phi_{c\nu} < 1.5$. These cuts also have a strong impact on the Wcj , Wjj , and W^+W^- backgrounds.

The remaining cuts of Tab. III are specific to “low mass” Higgs bosons, that is $M_H \lesssim 170$ GeV. We make strong cuts on the angle between the jet and charm $\cos\theta_{jc} < -0.5$ and between the lepton and neutrino $\cos\theta_{l\nu} < -0.8$. Above 170 GeV we use a set of “high mass” cuts shown in Tab. IV that loosen the angular cuts to $\cos\theta_{jc} < -0.2$ and $\cos\theta_{l\nu} < -0.4$, because boosts to the on-shell W bosons tend to push the peak of these distributions away from being back-to-back. The opening of these cuts is the main reason for the reduction in

TABLE III: Number of signal and background events per fb^{-1} of data for $m_H = 165$ GeV and $k_c = 4$ at a 14 TeV LHC, using common cuts (above line) and “low mass” cuts (below line).

Cuts	Signal	Wcj	WW	$t\bar{t}$	Wbj	Single top	$Wc\bar{c}$	$Wb\bar{b}$	Wjj
2 or 3 jets, 1 c tag, 1 l	259	85192	2090	17223	7635	15166	2995	1118	13331
$\cancel{E}_T > 20.0$ GeV	228	74798	1818	15694	6862	13755	2685	1016	12327
$E_{Tc} < 80$ GeV	224	53563	1582	9957	5143	10103	2153	803	9189
$p_{Tl} < 60$ GeV	216	40222	1304	7074	4323	8558	1716	615	6784
$ \Delta\eta_{cj} < 2.0$	184	29818	1214	5921	3185	4991	1426	539	5012
$\Delta\phi_{c\nu} < 1.5$	142	11393	223	1993	1216	1470	393	153	1618
$\Delta\phi_{jl} < 2.0$	126	8867	178	1364	961	1136	321	123	1175
$\cos\theta_{jc} < -0.5$	106	5178	78	846	488	740	160	70	659
$\cos\theta_{l\nu} < -0.8$	75	1875	42	181	170	145	73	31	198
$\cos\theta_l^0 < 0.2$	59	1179	28	147	117	109	44	21	138
$140 \leq M_{l\nu cj} \leq 170$	45	423	19	6	39	18	20	9	58

sensitivity at larger masses.

The final angular variable we consider is the angle θ_l^0 of Ref. [7]. θ_l^0 is the angle between the lepton and the boost direction of the initial W -boson in the Higgs boson rest frame. For “low mass” Higgs bosons we place a cut demanding $\cos\theta_l^0 < 0.2$. We find this angle is less effective in the “high mass” regime, and therefore do not apply the cut. Instead, we utilize the knowledge that the second W boson will be on-shell and impose a W mass reconstruction cut of $50 < M_{jc} < 85$ GeV on the search for “high mass” Higgs bosons. We notice that the peak of the reconstructed W mass is below the nominal value of 80.4 GeV due to our use of a small cone size in our jet reconstructions. It may be desirable experimentally to apply jet energy corrections and tighten this cut window, but we accept the reduction in efficiency in this analysis.

We show the invariant mass distribution $M_{l\nu cj}$ of background B , and a 165 GeV Higgs signal plus background $S + B$ in Fig. 3. We choose to leave some of the cuts looser than is optimal in order to have a significant region of pure background on both side-band regions of the invariant mass. This will allow a reasonably accurate *in situ* measurement of the background, and should greatly reduce systematic uncertainties. We finish by reconstructing the invariant mass of the $l\nu cj$ system, so that $140 \leq M_{l\nu cj} \leq 170$ GeV in the “low mass” region, and $m_H - 20 \text{ GeV} \leq M_{l\nu cj} \leq m_H + 10 \text{ GeV}$ in the “high mass” region.

From Tab. III, we see that the resulting signal to background ratio $S/B \sim 1/13$ for a 165 GeV Higgs boson when the charm tagging efficiency averages 48% ($k_c = 4$). Before examining the signal significance, we first demonstrate that Wcj background is an order-of-magnitude larger than any other background for all charm tagging efficiencies. In Fig. 4 we show the expected number of events after all cuts in 10 fb^{-1} of integrated luminosity for the signal and all backgrounds. With current b -fake rates, Wbj is slightly larger than the signal (though much smaller than Wcj), but quickly saturates. If k_c is large, then Wjj grows in importance, but is also still insignificant with respect to Wcj . Since the signal and direct Wcj have the same charm jet tagging efficiency, they scale together. Hence, our observation that luminosity

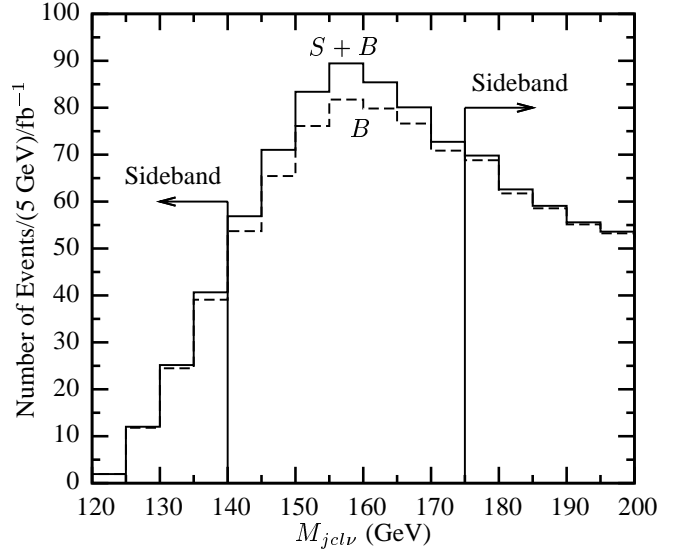


FIG. 3: Invariant mass of the $l\nu cj$ system for the background B , and 165 GeV Higgs boson signal S plus background $S + B$, for $k_c = 4$.

required for reaching a given significance will scale approximately linearly with k_c . All other backgrounds are small compared to the signal for any charm tagging efficiency, and backgrounds with two b -jets become less important as events with two tags are discarded.

Using the numbers in Tab. III, we find that if $k_c = 4$, a 165 GeV Higgs boson could be discovered at 5σ with 7 fb^{-1} of integrated luminosity. In general, we are interested in what significance can be reached as a function of Higgs mass, and what improvement in charm tagging efficiency is required to get there. In Fig. 5, we present the significance obtainable with 10 fb^{-1} of data at a 14 TeV LHC as a function of Higgs mass. With current charm tagging efficiency ($k_c = 1$), the $H \rightarrow Wcj$ channel plays a complementary role in the Higgs search, contributing 1.5 – 2.5σ to a combined analysis. With a modest improvement in charm acceptance ($k_c \sim 2$), corresponding to about 25% acceptance, the Wcj final state has comparable reach to WW fusion production with decay into $l^+l^-\cancel{E}_T$ for all Higgs masses. This is evident in

TABLE IV: Number of signal and background events per fb^{-1} of data for $m_H = 180$ GeV and $k_c = 4$ at a 14 TeV LHC, using “high mass” cuts after common cuts (top half of Tab. III) have been applied.

Cuts	Signal	Wcj	WW	$t\bar{t}$	Wbj	Single top	$Wc\bar{c}$	$Wb\bar{b}$	Wjj
$\cos\theta_{jc} < -0.2$	81	6759	114	1117	658	957	223	94	866
$\cos\theta_{l\nu} < -0.4$	72	4747	98	626	431	499	173	72	581
$50 \leq M_{jc} \leq 85$ GeV	56	1971	80	65	163	88	95	37	282
$m_H - 20 \leq M_{l\nu cj} \leq m_H + 10$	42	1167	50	40	93	53	52	20	163

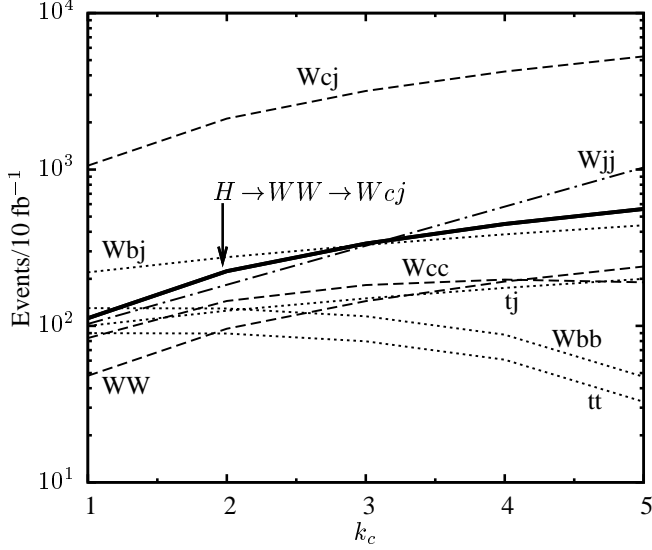


FIG. 4: Number of events in 10 fb^{-1} at a 14 TeV LHC for the $H \rightarrow Wcj$ signal (solid), and backgrounds from processes with charm jets (dashed), bottom jets (dotted), and light jets (dot-dashed).

Fig. 5, where we show the ATLAS WW -fusion reach extracted from Ref. [1], scaled to our estimate of the NLO K -factor after cuts. In addition, we show the ATLAS gluon-fusion prediction for $H \rightarrow l^+l^-\cancel{E}_T$ scaled to our NLO K -factor after cuts (1.3 vs. 1.9 used in Ref. [1]). If charm tagging efficiency could be raised to $\sim 50\text{--}60\%$ ($k_c = 4\text{--}5$), then the Wcj final state has comparable reach to dileptons+ \cancel{E}_T above 155 GeV. While improved charm tagging efficiency is important in its own right, it is clear the $H \rightarrow Wcj$ can play a role in the Higgs search comparable to existing channels.

At present, the LHC is operating at 7 TeV, which leads to a reduction in the cross-sections of both the signal and Standard Model backgrounds compared to our predictions at 14 TeV. In addition, the lower energies also lead to a softer spectrum for the jets and leptons. Therefore, in Table V we move the charm jet E_T cut from 80 GeV to 60 GeV. Once this cut is made, the optimal lepton p_T remains the same as in the 14 TeV analysis. As there is less energy in these events, the Higgs boson is less boosted and so decays in a more central region of the detector. Hence, the cut on $|\Delta\eta_{lc}| < 1.5$, for the 7 TeV analysis, has a greater effect on improving S/B as compared to that in 14 TeV analysis.

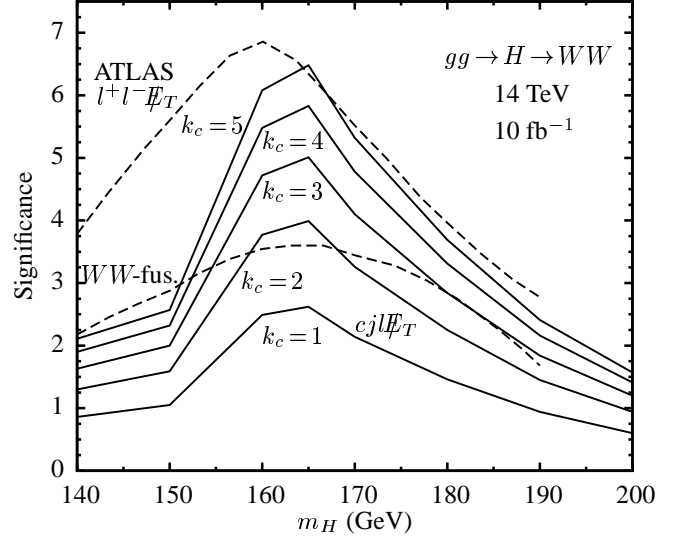
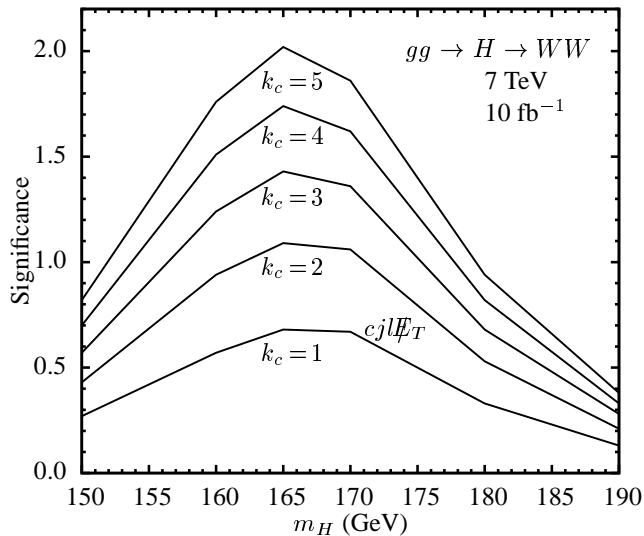


FIG. 5: Higgs signal significance obtainable at a 14 TeV LHC with 10 fb^{-1} of integrated luminosity vs. Higgs boson mass m_H in the $l\nu cj$ channel for various multiples of the current charm tagging efficiency k_c . ATLAS dilepton reach is shown (assuming a K -factor of 1.3) for gluon-fusion ($l^+l^-\cancel{E}_T$) and WW -fusion [1].

Similar to the 14 TeV analysis, the angular correlations between charm and the neutrino make the $\Delta\phi_{c\nu}$ cut important in reducing the single-top and standard model W^+W^- backgrounds. However, due to the lack of energy, the remaining angular cuts in the 14 TeV analysis would degrade the significance of the signal. Instead, we impose ΔR cuts shown in Table V that marginally improve the signal significance. Finally, we extract the Higgs mass with a 40 GeV window about the central value. Using the numbers shown in Table V we see that to obtain a 95% confidence-level exclusion limit for a $m_H = 165$ GeV we need a 13 fb^{-1} integrated luminosity for $k_c = 4$. In Fig. 6 we show the reach in the Wcj final state as a function of Higgs mass for various improvements k_c to charm tagging efficiency. For all masses and k_c the significance with 10 fb^{-1} of data ranges between $0.5\text{--}2\sigma$. Hence, Wcj should play a complimentary role in the 7 TeV LHC exclusion limits for a standard model Higgs boson.

TABLE V: Number of signal and background events per fb^{-1} of data for $m_H = 165$ GeV and $k_c = 4$ at 7 TeV LHC.

Cuts	Signal	Wcj	WW	$t\bar{t}$	Wbj	Single top	$Wc\bar{c}$	$Wb\bar{b}$	Wjj
2 or 3 jets, 1 c tag, 1 l	32	3812	245	46	1016	1406	906	345	932
$\cancel{E}_T > 20.0$ GeV	30	3522	232	45	957	1353	839	326	892
$E_{Tc} < 60$ GeV	24	1946	148	19	601	666	536	223	283
$p_{Tl} < 60$ GeV	19	821	81	7	271	368	256	106	88
$ \Delta\eta_{cj} < 1.5$	16	591	59	5	171	246	191	75	59
$\Delta\phi_{c\nu} < 1.5$	12	230	15	1.6	66	85	55	26	19
$2.9 < \Delta R_{jl} < 2.1$	10	162	11	1.2	49	57	35	18	14
$2.0 < \Delta R_{ln} < 3.0$	8	104	7	0.5	31	27	22	12	5
$m_H - 20 \leq M_{l\nu cj} \leq m_H + 20$	4.4	34	2.8	0.04	9	3	9	3.9	1.5

FIG. 6: Higgs signal significance obtainable at a 7 TeV LHC with 10 fb^{-1} of integrated luminosity vs. Higgs boson mass m_H in the $l\nu cj$ channel for various multiples of the current charm tagging efficiency k_c .

IV. CONCLUSIONS

We demonstrate the use of a new channel for the discovery of a Higgs boson of mass 140–200 GeV, $H \rightarrow W^+W^- \rightarrow l\nu cj$. By utilizing a dedicated charm tagger we gain experimental access to angular correlations not observable in the dilepton+ \cancel{E}_T analysis that can be used to reduce the Wjj backgrounds to an acceptable level. This could allow a 5σ discovery of a Higgs boson near the WW threshold with $\sim 7 \text{ fb}^{-1}$ of integrated luminosity at a 14 TeV Large Hadron Collider in the Wcj channel. If the current 7 TeV run of the LHC delivers 10 fb^{-1} of data, then this channel could help rule out a standard model Higgs boson with mass between 150–190 GeV.

While one goal is to motivate the creation of a dedicated charm tagger, this analysis is robust without any

improvements to existing algorithms. In particular, the luminosity required for 5σ discovery scales inversely with charm tagging efficiency. Therefore, utilizing the charm contamination of existing b -tagging algorithms as a poor charm-tagger ($\epsilon_c \sim 12\%$ for typical jet transverse energies) already is enough to provide 1/2 the significance of WW -fusion searches, and 1/5 the significance of existing gluon-fusion searches to dileptons plus missing transverse energy. With a small improvement to charm acceptance, the Wcj channel has comparable reach. Wcj provides a window into the Higgs searches with significantly different backgrounds and low correlation to other channels.

We conclude with the observation that the angular correlations in the Higgs signal lead to a fairly soft missing energy signature. In this analysis we choose a cut of $\cancel{E}_T > 20$ GeV, as used in the recent ATLAS projections for large-mass Higgs reconstruction [1]. We have also investigated the effects of increasing the \cancel{E}_T to 30 GeV, and find the significance declines by only 5%. Hence, our conclusions remain robust if higher instantaneous luminosities force the use of harder cuts.

Given the significant correlations between the Higgs decay products, it seems likely that more complicated multivariate techniques, such as neural network searches, could improve the prospects for searches in the Wcj final state. This should be pursued for integration into the current 7 TeV Higgs searches at the LHC. Having demonstrated the promise of the semi-leptonic channel at the LHC, it will be useful to see how this channel can contribute to the ongoing Higgs boson searches at the Fermilab Tevatron.

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